Fixed target muon experiments for dark sectors

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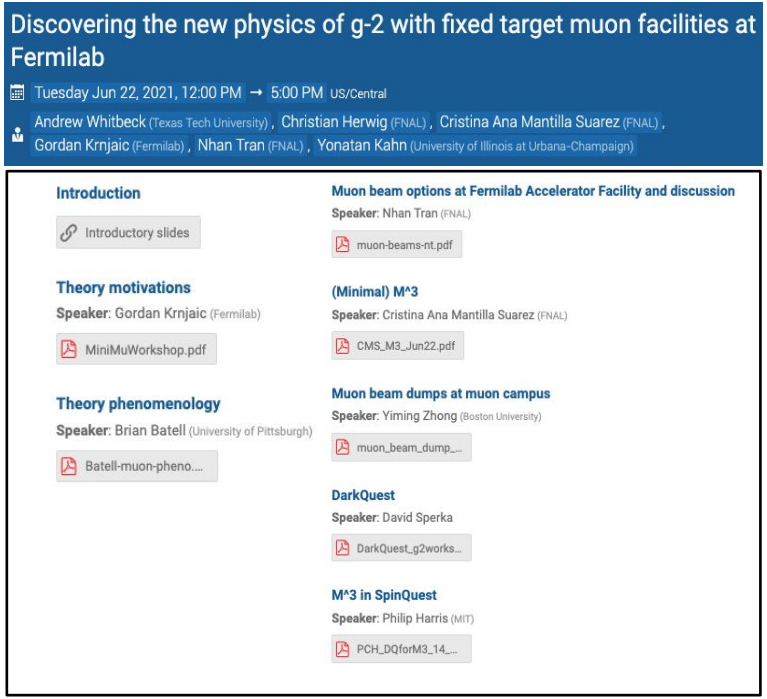
Outline

Motivation: g-2 and dark matter

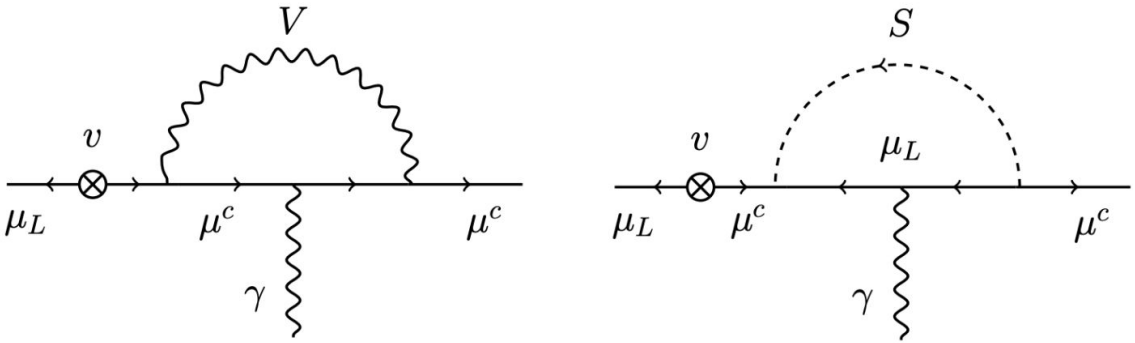
Light new physics g-2 program

- X to ee,γγ
- X to Invisible
- X to μμ

https://indico.fnal.gov/event/48936



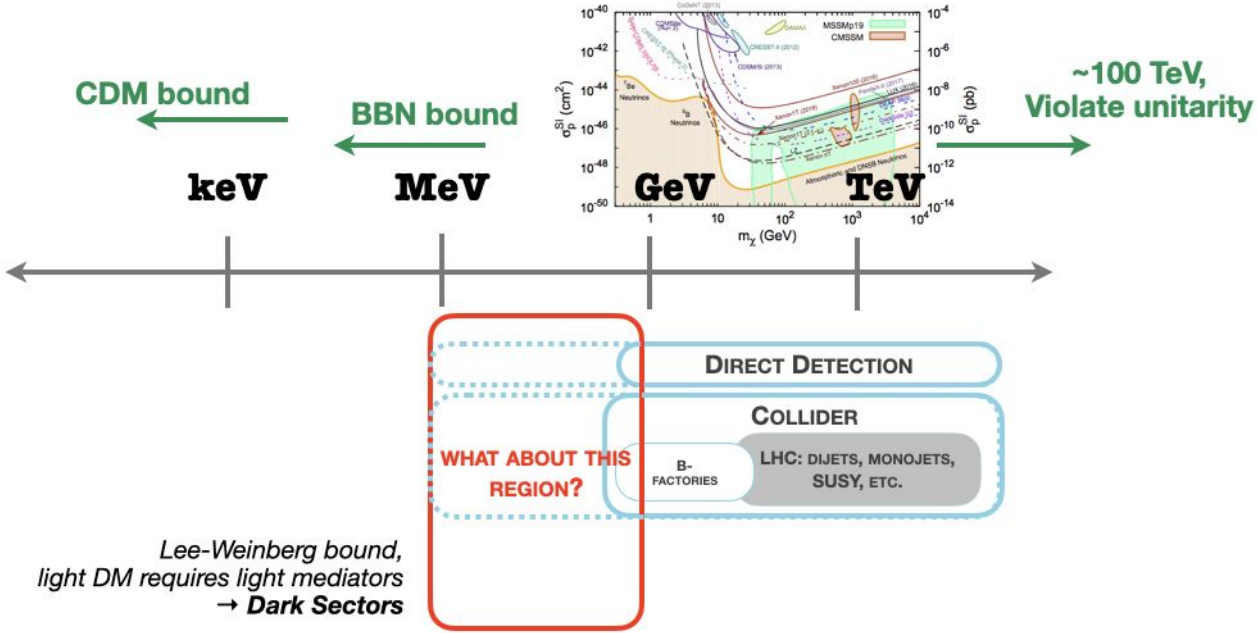
Motivation: light new physics for g-2



If it contributes to g-2, it couples to the muon!

Thermal dark matter & accelerators

See for example,
DOE Dark Matter New Initiatives Report



NORMAL MATTER LIVES HERE. WHY NOT DM?

+ Curious results…
muon g-2, proton radius puzzle, KTEV excess, astrophysical inconsistencies

Thermal dark matter & accelerators

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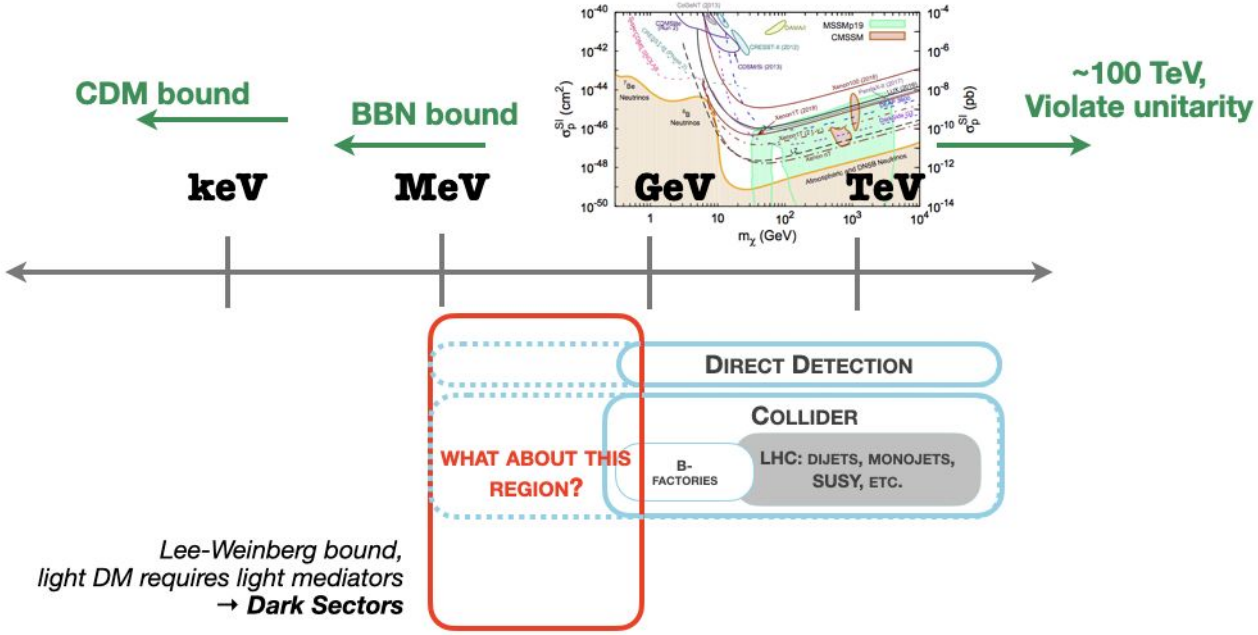

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RF Accelerator DM agora in planning!

A No-Lose Theorem for Discovering the New Physics of $(g-2)_\mu$ at Muon Colliders

Rodolfo Capdevilla, David Curtin, Yonatan Kahn, Gordan Krnjaic

arXiv:2101.10334

1. **Present day confirmation:**

   Assume the $(g-2)_\mu$ anomaly is real.

2. **Discover or falsify low-scale Singlet Scenarios $\lesssim$ GeV:**

   If Singlet Scenarios with BSM masses below $\sim$ GeV generate the required $\Delta a_\mu^{\rm obs}$ contribution [38], multiple fixed-target and B-factory experiments are projected to discover new physics in the coming decade [39, 66–73].

3. **Discover or falsify all Singlet Scenarios $\lesssim$ TeV:**

   If fixed-target experiments do not discover new BSM singlets that account for $\Delta a_\mu^{\rm obs}$, a 3 TeV muon collider with 1 ab^{-1} would be guaranteed to directly discover these singlets if they are heavier than $\sim 10\,\text{GeV}$.

   Even a lower-energy machine can be useful: a 215 GeV muon collider with 0.4 ab^{-1} could directly observe singlets as light as 2 GeV under the conservative assumptions of our inclusive analysis, while indirectly observing the effects of the singlets for all allowed masses via Bhabha scattering.

…Steps 4-5 are related to muon colliders…

Motivation for g-2 and dark sectors

Light solutions possible for g-2

Muon beams are needed to explore light solutions to g-2

Muon beams could also provide window to light dark sectors

Light solutions to g-2 could be related to light dark sectors

Physics program for light solutions for g-2

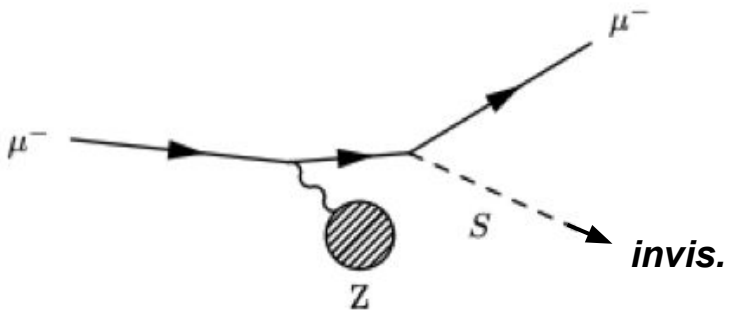
Credit: Brian Batell

	Invisible			Visible			
final state/ mediator	Long-lived	neutrinos $\nu\nu$	DM $\chi\chi$	photons $\gamma\gamma$	electrons e^+e^-	muons $\mu^+\mu^-$	hadrons $\pi\pi, \ldots$
vector	no(?)	yes	yes	no	no(?)	yes* ($m_V > 2m_\mu$)	no(?)
	• $L_\mu - L_\tau$ gauge boson: UV complete, automatic coupling to neutrinos, easy to couple to DM. (* $m_V > 2m_\mu$ constrained by dedicated *BABAR* search) • Challenging to build viable models with sizable couplings of vector mediator to electrons or hadrons (gauge anomalies, constraints from neutrino physics)						
scalar	yes ($m_S < 2m_\mu$)	yes	yes	yes ($m_S < 2m_\mu$)	yes ($m_S < 2m_\mu$)	yes ($m_S > 2m_\mu$)	yes ($m_S > 2m_\pi$)
	• All minimal signatures can be realized in scalar simplified models. • UV complete models require new SM-charged states above weak scale with special flavor structure (such states can in principle affect (g-2) • More phenomenological studies needed to chart the parameter space						
signature	missing momentum			prompt or displaced resonance			

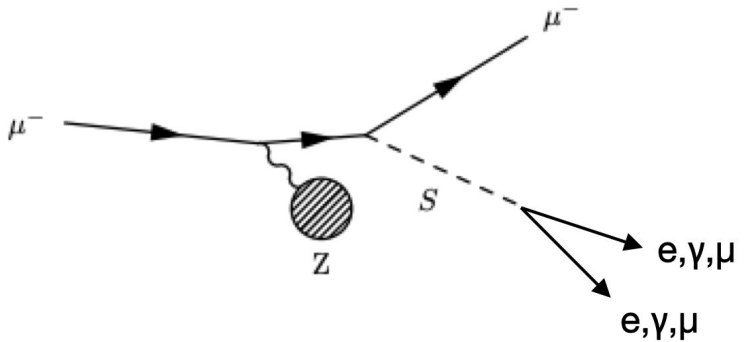
Legend:

Yes = allowed and available phase space
No (?) = allowed, but you have to try hard to evade current bounds
No = definitely not allowed

Fixed-target signatures



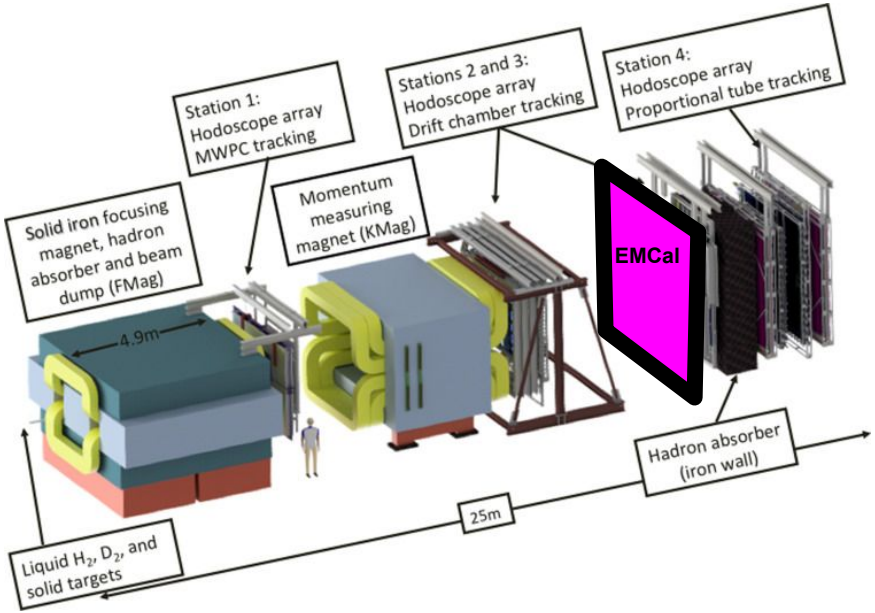
Muon missing momentum



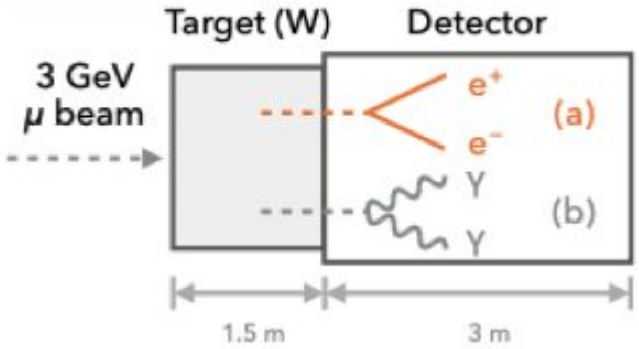
Muon fixed-target or beam dump
ee or γγ are displaced
μμ is prompt

Decaying to ee,γγ via loops

Berlin, Gori, Schuster, Toro, arXiv:1804.00661
Blinov, Kowalcyzk, Wynne, arXiv:2112.09814
Chen, Pospelov, Zhong, arXiv:1701.07437



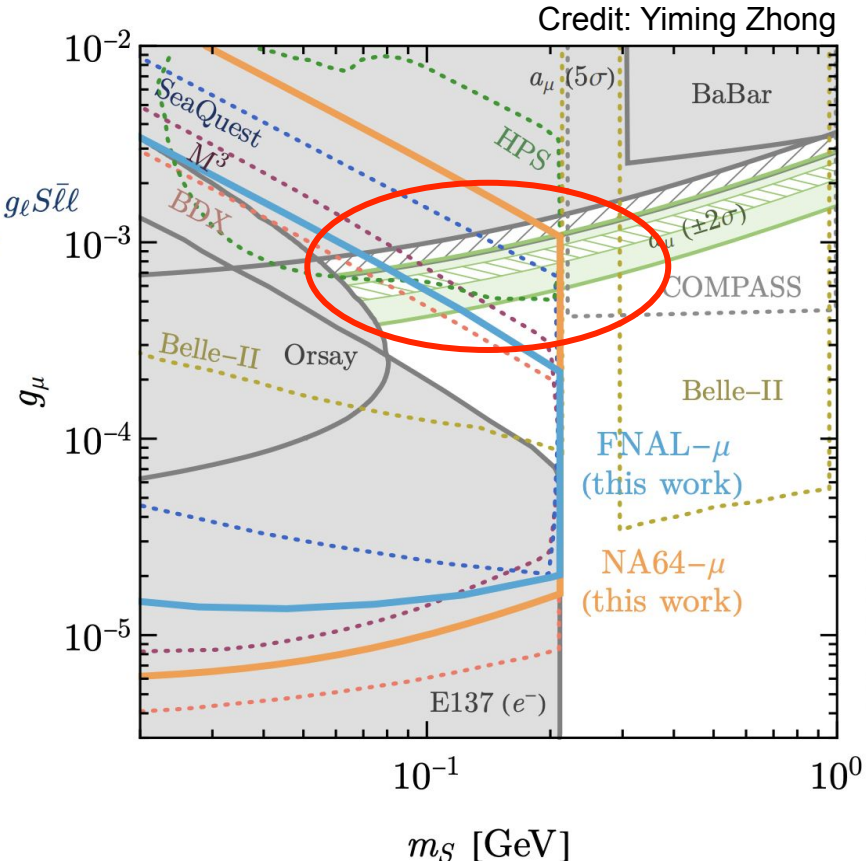
DarkQuest - extension of SpinQuest with EMCal
~1e18 protons; secondary muon beam dump
Fermilab 120 GeV Main Injector beam



Dedicated 3 GeV muon beam dump
~1e14 μ+
(at Fermilab muon campus)

Decaying to ee,γγ via loops

$$\mathcal{L} \supset -\sum_{\ell=e,\mu,\tau} g_\ell S\bar{\ell}\ell$$



Essig+ '10
Battaglieri+ '14
Batell+ '16
Kahn+ '18
Berlin+ '18
Marsicano + (YZ) '18

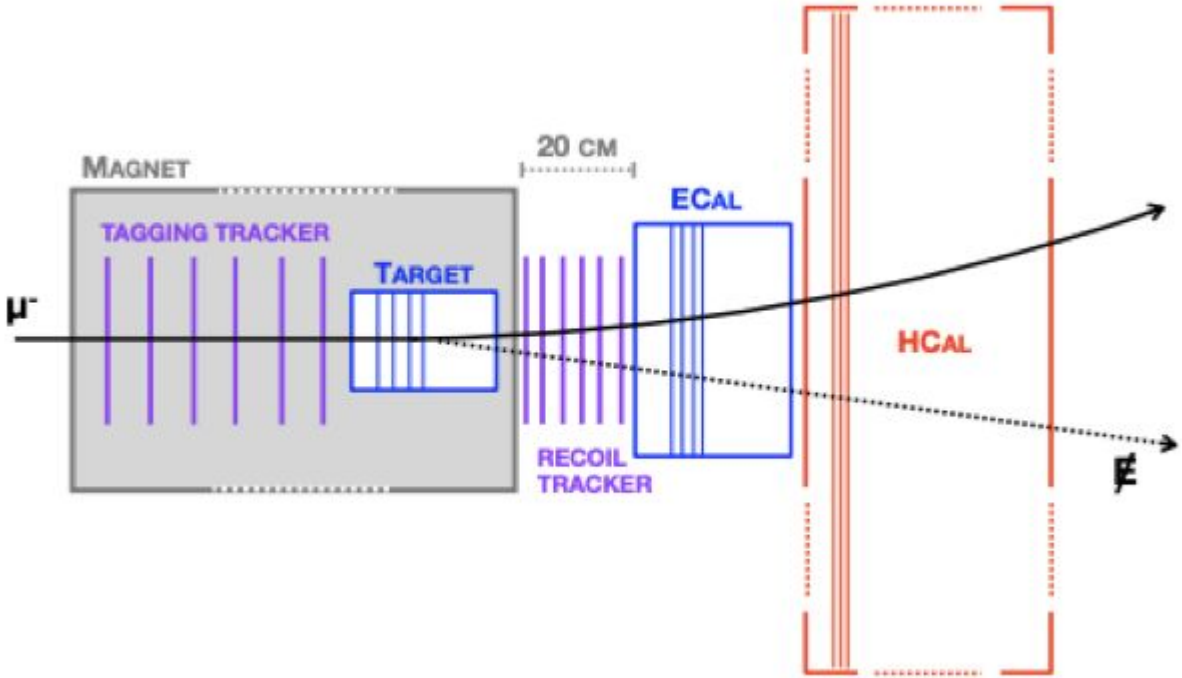
Example model
X → e+e-

Closes of most of remaining g-2 phase space below $2m_\mu$

See references (previous slide) for similar sensitivity to γγ final states as well

Decaying invisibly

Kahn, Krnjaic, Tran, Whitbeck
arXiv:1804.03144

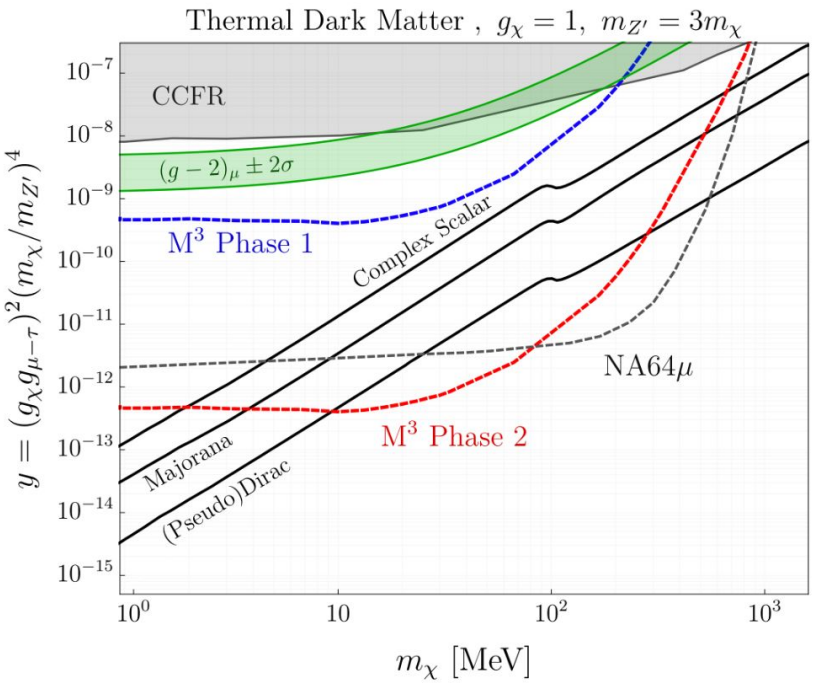


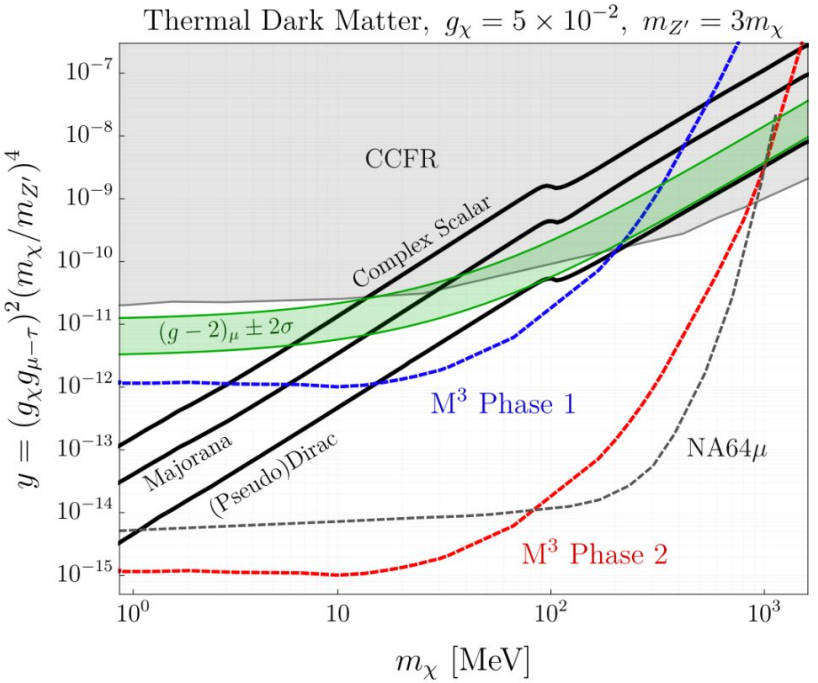
~15 GeV muons, Need to individually reconstruct

outgoing muon loses >40% of momentum

Phase 1: 1e10 Muons on Target, at FNAL test beam facility
Phase 2: 1e13 Muons on Target, at FNAL NM 120 proton line

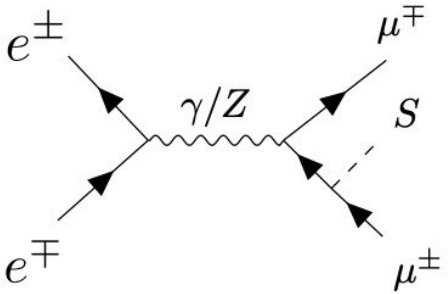
Decaying invisibly



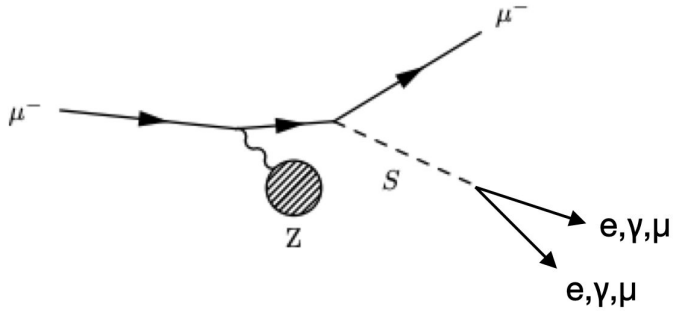


Left: larger couplings to dark matter, g_χ, than the right plot
Right plot show scenario where g-2 solution explains the dark matter relic density

Decaying to μμ



B-factory searches for 4μ



Fixed target prompt search difficult! (Maybe LArTPC?)

Searches require very good invariant mass precision to avoid radiative backgrounds ($\gamma^* \rightarrow \mu\mu$) ~ O(%) level

Broader worldwide program

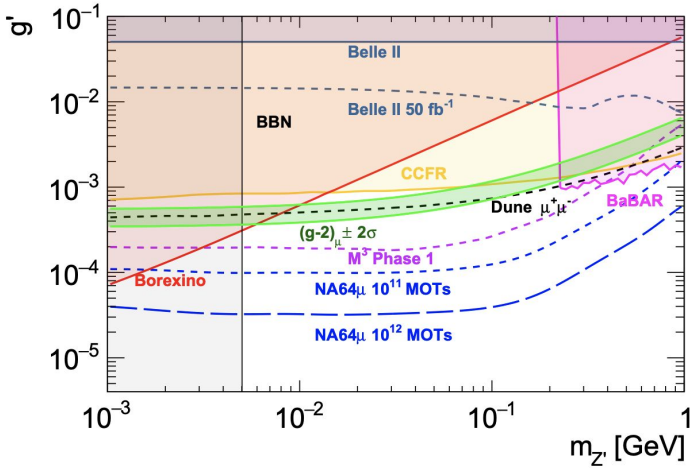
Prospects in the search for a new light Z’ boson with the NA64μ experiment at the CERN SPS
arXiv:2110.15111

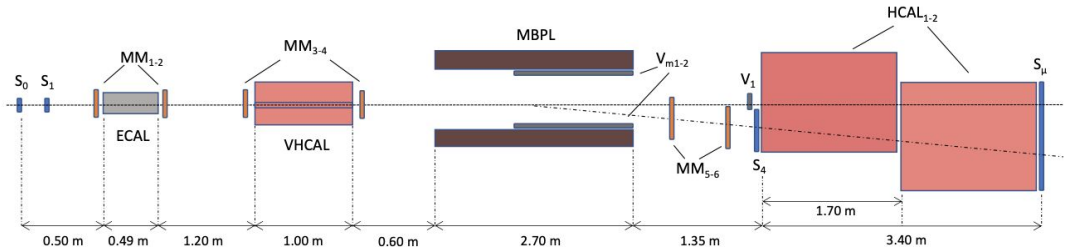
- Missing momentum technique
- Pilot run planned in 2021

Rare Kaon experiments like NA62 potentially also sensitive in the missing momentum mode (arXiv:1902.07715)

DUNE neutrino tridents have sensitivity as well in long term
arXiv:1902.06765

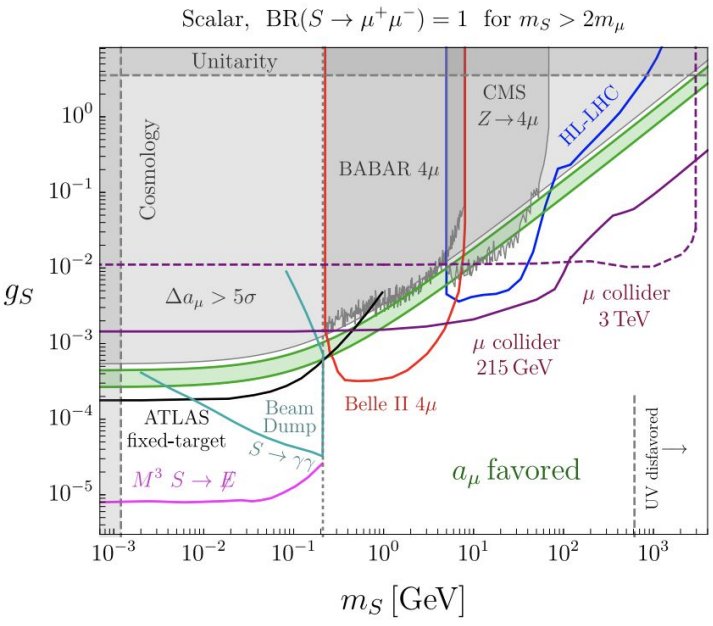
ATLAS “muon missing momentum” searches (HL-LHC timeline)
arXiv:1906.09272

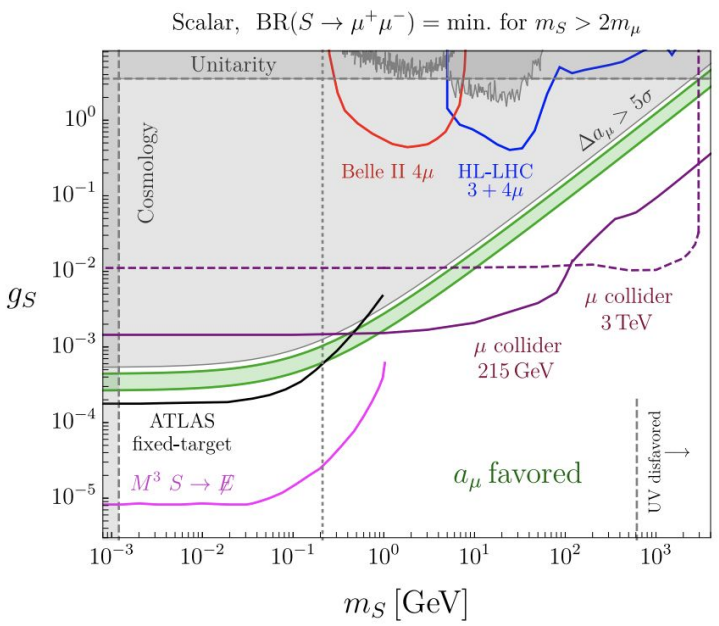




Broader worldwide program

Capdevilla, Curtin, Kahn, Krnjaic
arXiv:2112.08377





Left: maximal coupling to muons
Right: minimal coupling to muons

Outlook

There are light new physics solutions related to g-2

Sub-GeV searches are near-term next step towards comprehensive g-2 exploration

Potentially related to dark sectors

A program requires coverage of invisible decays and ee,μμ,γγ final states

Suite of complementary and modest planned and proposed experiments needed

backup

Broader worldwide program